STATISTICAL PROCESSING OF PLASMA JET IMAGES FOR VISUALIZATION OF FLOW INSTABILITIES

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The structure and stability of a thermal plasma jet were studied on the basis of statistical analysis of images of a plasma jet taken by a fast shutter camera. The space distribution of the mean value and the standard deviation of image brightness were evaluated from a sequence of images. The short exposure time ensured imaging of the momentary state of the jet while analysis of a sequence of images provided information about jet fluctuations. Effect of arc current was investigated. Arc power increase led to higher fluctuations of the jet, although it caused increase of the jet length.

1. Introduction

Thermal plasma is a state any substance turns into when heated to temperatures of approximately several thousands Kelvins. Such a powerful agent is useful in a number of industrial applications for a melting, cutting, decomposition of waste, modification and renovation of surfaces. A common method of a thermal plasma generation is driving of a plasma forming gas through a chamber where an electric arc burns. Gas heated and ionized by the arc flows out into the ambient atmosphere through a nozzle. The generated plasma jet is used for a heating of a treated part. Understanding of flow characteristics is important for a process control as flow stability and structure have a big influence on the process of the energy transfer. An interaction of a high velocity and low density plasma flow with an ambient atmosphere causes instabilities in boundary layer and leads to waving and fluttering of the jet similar to a flame tip flicker, though much faster and brighter.

Time averaged images of the thermal plasma jet, taken with long exposure time, are often used for characterization of mean geometrical parameters of the jet (length, width, orientation) together with its radiation intensity [1, 2]. Although these parameters relate to effective values, they are not representative enough for a plasma jet investigation because high frequency fluctuations are blurred in these images. There are some parameters for the indirect plasma stability investigation: acoustic noise, power fluctuations and local fluctuations of plasma radiation. Direct methods like Particle Image Velocimetry, high speed imaging, Laser Doppler Anemometry and others are very informative but too complicated for using as routine control.

Short exposure images are used for giving a conception of the jet dynamics [3, 4]. Use of such images for statistical analysis can provide general parameters for less complicated description of the plasma jet. A set of short exposure images can be averaged and provide the same information as the time averaged image. Moreover the set of images can be used for investigation of brightness deviation. This can provide information about distribution of plasma jet fluctuation and thus characterize its stability.

2. Description of the statistical image processing

In contrast to common statistical methods in the image analysis, which are based on a processing of the neighbor pixels in a picture, this method uses an interframe operation. An array of brightness of pixels with the same position in several images of the plasma jet is evaluated independently. Processing of an image set is schematically described in Fig. 1 and is considered in details in the following. The pictures demonstrate every step of processing and are obtained as a result of application of the equations denoted above each picture. The equations describe evaluation of brightness value of some particular point and must be applied to each point of the image separately.

The set of images of the plasma jet represents raw data (Fig. 1a). The images of the jet can be taken randomly in the time as there is no synchronization requirement for the statistical treatment. The mean jet image is created by an averaging of brightness in each pixel through the whole set of the images (Fig. 1b). Main orientation of the plasma flow as well as geometry of the plasma jet can be seen on such images. In Fig. 1c there is the next step of the processing. It is an example of an image of the standard deviation (STD image) of brightness. It is evaluated as the mean square deviation of brightness of each pixel of the whole set of the primary images.

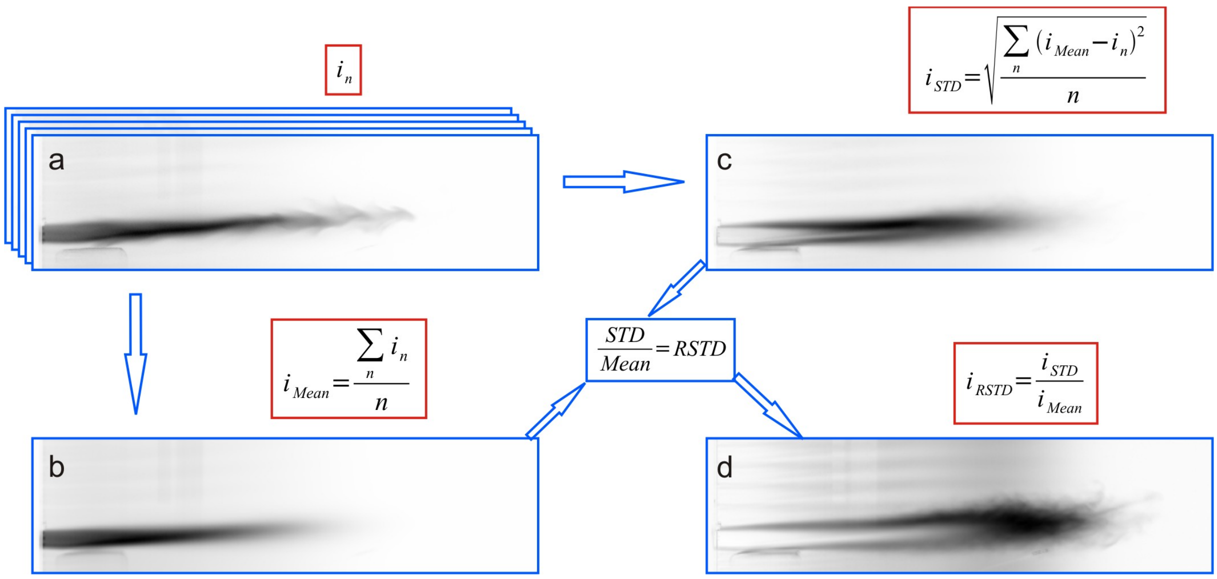

Figure. 1. Illustration of the image processing method.

Generally brightness fluctuation depends on both intensity of local fluctuations and brightness of the plasma jet in particular region. It means that only fluctuations of a part of the jet with the highest radiation intensity are visible. The way to eliminate the dependence on absolute brightness is an evaluation of the standard deviation of a relative brightness as it is expressed by the following equation:

$$x_{RSTD}=\sqrt{\frac{1}{n}\sum_n\left(\frac{x}{x_{Mean}}-1\right)^2}=\sqrt{\frac{1}{n}\sum_n\left(\frac{x-x_{Mean}}{x_{Mean}}\right)^2}=\frac{1}{x_{Mean}}\sqrt{\frac{1}{n}\sum_n\left(x-x_{Mean}\right)^2}=\frac{x_{STD}}{x_{Mean}}\quad , \quad (1)$$

where X_{RSTD} – the relative standard deviation of the local brightness, X_{Mean} – the mean value of the local brightness, n – a number of images processed, X – the local brightness in the original image of the plasma jet, X_{STD} – the standard deviation of the local brightness. In the last step of the processing the standard deviation of brightness of each pixel is related to the average brightness value of the corresponded pixel. A result is the image of the distribution of relative standard deviation of brightness (RSTD image), which visualize plasma flow unsteadiness (Fig. 1d).

3. An analysis of the processing

There are some critical parameters which must be considered in order to produce reliable results. The first parameter is a number of the photographic images which are used for production of the mean and RSTD images. In the work it was determined a posteriori. Fig. 1d is based on processing of 2 000 primary images. The images in Fig. 2 are based on a lower number of the photos. While the low statistic images are more illustrative as a particular position of the plasma jet tip is visible, the high statistic is more convenient for analysis, comparison and unbiased characterization.

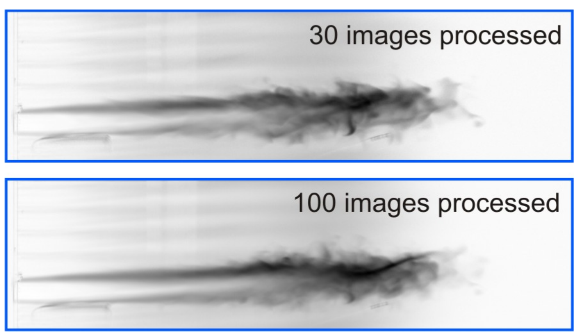

Figure. 2. RSTD images based on processing of 30 and 100 original images

The second parameter is the exposure time of the photographic images of the plasma jet. It is defined by a rate of plasma fluctuations. Adapting the Nyquist-Shannon-Kotelnikov sampling theorem, the RSTD image is the complete representation of the brightness fluctuation if the exposure time of the primary photographs is at least two times shorter than the fastest fluctuations period. Fluctuations which are much faster than exposure are suppressed approximately proportionally to a ratio between the fluctuation period and the exposure time. Then the imaging exposure time (t_{exp}) defines a higher limit frequency of the visualized fluctuation (f_{limit}), which is about

$$f_{limit} = \frac{1}{t_{exp}} \quad (2).$$

It can be used for an investigation of the fluctuations in a particular frequency range.

Last important parameter is a sensitivity of a camera used for photographing of the plasma jet. It is important to check which part of the plasma jet the camera is able to record at particular exposure time. With low energy jets or with extremely short exposure time it could happen that only a steady core of the plasma jet will be recorded by the camera while unstable boundary will be invisible.

4. Experimental arrangements

A plasma jet generated by a water stabilized DC arc plasma torch [5] was investigated. The jet is formed by water vapor heated in the arc. The arc starts from a graphite cathode inside the torch, burns in an arc chamber with water stabilization, and, after leaving of the arc chamber through a nozzle, connects to an anode, which is situated after the nozzle (Fig. 3). The nozzle exit diameter (5.6 mm) defines the diameter of the plasma jet at the exit. The arc current can be change in range 300 - 550 A (total power of 70 - 160 kW).

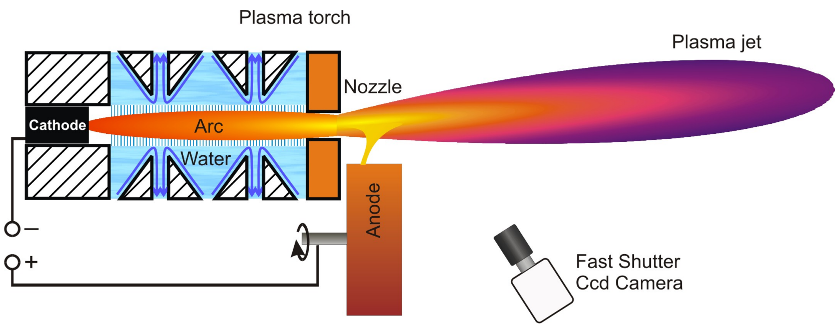

Figure. 3. Experimental set-up.

For plasma jet imaging fast shutter CCD camera Sensicam by PCO.imaging was used. The camera is able to take sequence of images with resolution 1024x1280 at exposure time down to 100 ns. Plasma jet was imaged from one side as it is shown in Fig. 3. For the investigation of influence of the torch parameters on plasma jet stability a sequence of 2000 images with resolution of 300x1200 pixels was taken with exposure time of 500 ns. Fluctuations of the jet are known to have the highest frequency of approximately 100 kHz, which means that their period is much longer than the exposure time. For the investigation of the plasma jet instabilities in particular frequency range a sequence of 500 images was taken at exposure time of 10 ms, 0.3 ms and 10 µs. Processing by a MATLAB code on a computer with P2600 processor was as fast as 4 images per second. It is believed that by an optimization of the code it is possible to achieve the camera imaging rate (7-10 images per second) for an efficient online application.

5. Example of results

As it was mentioned before for the investigation of the space distribution of the fluctuations in different frequency ranges sequences of 500 images was made at three different exposure time (Fig. 4a, b, c). According to Eq. 2 the upper limit frequencies of visualized fluctuations were 100 Hz, 3.3 kHz and 100 kHz respectively. By subtraction of image a from image b fluctuations in the range from 100 Hz to 3.3 kHz can be visualized (Fig. 4e) and by subtraction of image b from image c the visualized fluctuation frequencies can be limited in the range 3.3 - 100 kHz (Fig. 4f).

The first image demonstrates slow fluctuations caused by an anode surface vibrations with a frequency of 50 Hz. These vibrations have considerable influence on the nearest part of the jet, while downstream parts are almost unaffected.

The image in Fig. 4e shows fluctuations in the range 100 Hz - 3.3 kHz. It is the brightest one among images d-f, which means that in this frequency range the fluctuations are strongest. Anode

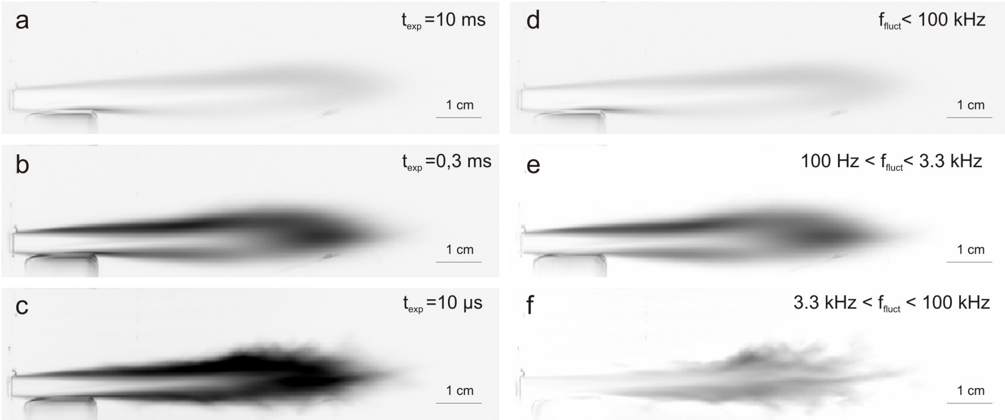

Figure. 4. Space distribution of the jet fluctuations in different frequency ranges

surface visibility is caused by the bright arc attachment to the anode, which is in continuous streamwise and counter streamwise movement. Particularly interesting phenomenon are high intensity fluctuations on the top boundary of the plasma jet. They could be caused by both the strong interaction of the plasma jet with ambient air and the influence of the anode attachment.

Fig. 4f corresponds to the fluctuations in the range 3.3-100 kHz. It turned out, that 500 images were not enough for good visualization of these fluctuations. The differences from the image in Fig. 4e, however, are clear. The fastest fluctuations correspond to later developing of the plasma jet. There are no fluctuations in the anode region.

For an investigation of an arc current influence on stability of the plasma jet the sequence of 2000 images were processed. Mean and RSTD images are presented as indexed (color map) images in order to increase contrast and distinctness. Color in such pictures corresponds to brightness, as it is shown on the color scale on the right.

In Fig. 5 RSTD and mean images of the plasma jet are presented for arc currents 350 A, 450 A and 550 A (total powers 90 kW, 130 kW and 160 kW). The red and blue lines indicate end of a visible part of the averaged jet and fluctuations of the jet. The yellow line indicates a real mean length of plasma jet calculated by averaging of lengths of the visible part of the jet in each picture of the sequence.

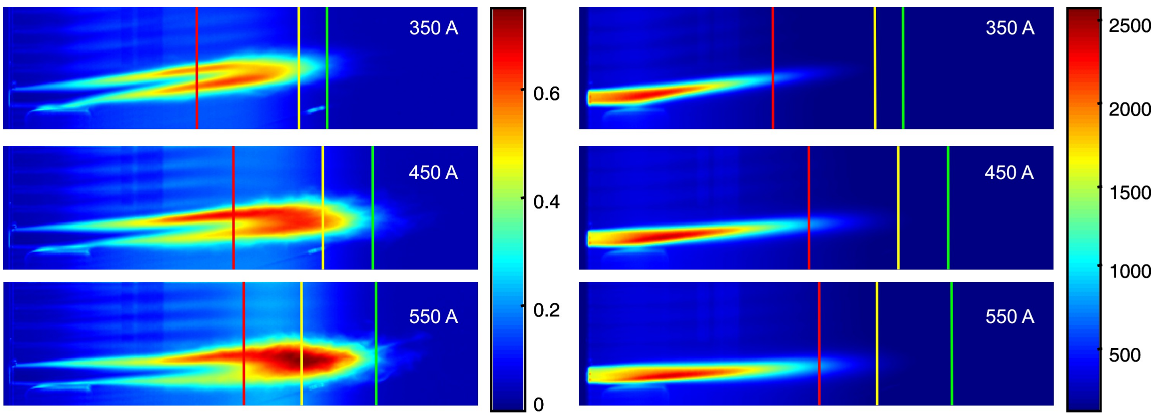

Figure. 5. Arc current effect on the plasma jet.

An increase of arc current from 350 A to 450 A leads to an increase of length of the averaged jet, lengthening of instabilities region as well as increase of mean length of the jet. Further current increase leads to slight increase of length of the averaged jet and minor shift of instabilities edge. The mean length, however, decreases significantly and coincides with the substantially intensified core of fluctuation region.

It could mean that at 550 A an intensive mixing with ambient air is a prevalent process in cooling of the plasma jet. Thus the arc current of 450 A seems to be the preferable regime as the plasma jet is more stable than at 550 A but much longer than at 350 A.

5. Conclusion

The method of statistical processing of the images of the plasma jet was explained. The method can be used for investigations of fluctuations and instabilities of flame-like radiative flows. Frequency range of the studied fluctuations can be specified and controlled by the exposure time of the imaging. Example of study of instabilities of the thermal plasma jet generated by the water stabilized arc plasma torch was given. The slowest fluctuations were caused by the anode surface vibrations having significant influence in the vicinity of the anode only. The most intensive fluctuations have frequencies in the range of 3.3 - 100 kHz. For the common torch geometry the arc current 450 A was found to be the most appropriate because the stablest plasma jet was observed.

Acknowledgments

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